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MARANGONI AND DOUBLE-DIFFUSIVE CONVECTION IN A FLUID LAYER UNDER MICROGRAVITY

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This grant was awarded on 01/12/92 for a period of three years to 30/11/95 with annual renewals. It was granted a no-cost extension to 31/08/96. Within this period, we have accomplished the following tasks:

1. Interactions Between Surface Tension-Driven and Double-Diffusive Instabilities

1.1. Marangoni and Double-Diffusive Instabilities

The effects of surface tension on the onset of convection in a layer of stably stratified fluid being heated from below have been investigated experimentally and theoretically in terms of linear stability analysis. The theory predicts a much lower critical thermal Rayleigh number for the onset of convection when the Marangoni instability is taken into account. The experimental results show general agreement with the theory. Furthermore, at gravity levels as low as $10^{-4}\ g_0$, where g_0 is the gravity at sea level, the double-diffusive effects are of equal importance as the Marangoni effect in destabilizing the fluid layer. Results of this research appeared in Tanny, Chen, and Chen (1995).

The effect of cross-diffusion on the stability of the system was studied by linear stability analysis. Results show that the nature of instability, whether oscillatory or steady convection, depends on the product χK, where χ is the separation ratio and K is a constant involving material properties. For a layer being heated from below, if $\chi K < 0$, gravity of small magnitude can enhance the stability. For $\chi K > 0$, however, gravity is always destabilizing. Results of this research appeared in Chen and Su (1994).

1.2. Salt Finger Convection Induced by Thermal and Solutal Capillary Motion

Experiments were conducted in shallow and deep stably stratified fluid layer consisting of ethanol-water solutions with 100% ethanol at the free surface. A thermal capillary motion is first generated on the surface by a small lateral temperature difference, 1-2°C. As the motion develops, it is being modified by the solutal effect on the surface tension gradient. This general circulation brings warmer and more concentrated fluid over cooler and less concentrated fluid. As a consequence, salt-finger convection is generated. These salt fingers appear as longitudinal rolls made visible by seeding the fluid with aluminum particles. Numerical simulations indicate that such a phenomenon can occur at microgravity levels. This phenomenon is best investigated in a space experiment. Results of this research were reported by Chen and Chan (1996) at the Third Microgravity Fluid Physics Conference and by Chen and Chen (1996a) at the Nineteenth International Congress of Theoretical and Applied Mechanics in Kyoto. A manuscript has been submitted to the *Journal of Fluid Mechanics* (Chen and Chen 1996b).

2. Effect of Gravity Modulation on the Stability of Convection in a Vertical Slot

2.1. Numerical Simulations

A finite difference code was developed to study the effect of gravity modulation on the convection of a fluid contained in a vertical slot being heated laterally. Particular attention was paid to the onset of vertical arrays of convection cells and their subsequent development. We first applied the code to high Prandtl number fluids with constant and variable viscosity, and the results compared favorably with experimental data obtained earlier. These results are reported in Jin and Chen (1996a, 1996b, respectively). Then, the code was used to examine the effect of gravity modulation on the onset of multi-cellular convection in fluids of low and high Prandtl numbers. It was found that the strongest effect is produced by g-modulations of low frequency and large amplitude. These results are reported in Jin and Chen (1996c).

2.2. Stability Analysis

In view of the simulation results, linear stability analysis has been applied to the g-modulation problem with special emphasis on the low-frequency and high-amplitude regime. The equations of the eigenvalue problem involve time-periodic coefficients, and Floquet theory is used for the solution of the problem. The process of solution requires integration in the time domain over one modulation cycle. When the frequency of modulation is low, the integration scheme requires a large number of time steps. This requires a long computation time and may incur unacceptable round-off errors. An alternative method suggested by Sinha and Wu (*Journal of Sound and Vibration* **151**, 91-117, 1991) was used. With this method, the state vector and periodic matrix are expanded into Chebyshev polynomials, and these functions can be evaluated at the end of the period without integration. The accuracy of the results can be improved by including more terms in the expansion. We found this method very useful in obtaining results for nondimensional frequencies as low as 20. For Pr = 1.0, the results show that the marginal stability curve is bimodal. At certain values of the modulation amplitude, there exist instabilities of two incommensurate wavelengths at the same critical Grashof number. Results of this investigation are given in Chen and Chen (1997), which is now under preparation.

4. Numerical Simulations

4.1. Finite Difference Method

A simulation using a two-dimensional, transient, finite element difference method (FDM) has been implemented. The algorithm can handle convection driven by surface-tension gradients and buoyancy. The algorithm is implemented on a parallel machine using a multiple program-multiple nodes method. To properly simulate high Rayleigh and Marangoni numbers, we sub-divided the domain into regular and singular subdomains. A very fine grid was used in the singular subdomain, while a coarse grid was used in the regular subdomain. This was implemented and tested. The theory and implementation of the regular and singular subdomains are given in detail by DeSilva and Chan (1997).

We applied the FDM algorithm to investigate the oscillatory onset of double diffusion found by Chen and Su (*Physics of Fluids A* **4**, 2360-2367, 1992). The underlying physics of the oscillatory motion is clearly demonstrated. The nonlinear evolution of perturbation was also examined. The simulation provides further understanding of the interactive effects between Marangoni and double-diffusive instabilities. The kinetic energy equation was derived. Each term in this equation can be interpreted physically as a source and sink. Each term is evaluated using the obtained numerical solution, providing a better understanding of the mechanisms of the instabilities.

In a series of experiments (see §1.2), we observed the generation of salt-finger convection due to capillary motion on the surface of a stably stratified fluid layer. When a stably stratified fluid layer is heated and cooled on the left and right sidewalls, respectively, the convection driven by surface-tension gradients causes a recirculation and creates a density inversion situation, a favorable condition for salt-finger convection. Using the FDM algorithm, we studied the cause of the salt-finger convection. It was found that, as the heating and cooling of the sidewalls start, two counter-clockwise vortices are established due to thermocapillarity. These vortices bring high-concentration solution to the free surface, creating a nonuniform concentration on the free surface. Near the hot (left) wall, the concentration on the free surface produces a surface-tension force opposing the thermocapillarity. However, the concentration on the free surface near the cold (right) wall reinforces the thermocapillarity. Consequently, the vortex near the hot wall decays while the vortex near the cold wall grows, which greatly distorts the temperature and concentration fields. It is the vortex near the cold wall that is responsible for the top-heavy situation that then leads to salt-finger convection. More numerical simulations are being performed to investigate the phenomenon. Results of this research were reported by Chen and Chan (1996) at the Third Microgravity Fluid Physics Conference.

4.2. Boundary Element Method

Steady-State Cross-Diffusion Solver

We have successfully implemented the BEM algorithm for the steady-state cross-diffusion equations. The algorithm is for two dimensions. Using this two-dimensional algorithm, we simulate a one-dimensional case, where an analytical solution is possible. It was found that the BEM results exactly match those of the analytical solution. The important thing is that eight boundary nodes (which means eight boundary elements) were used in this calculation. This demonstrates the accuracy of the BEM algorithm.

In the course of implementing the steady-state cross-diffusion solver, we had to develop and implement a switching process. This switching process can be directly applied to the simulation of double-diffusive convection with cross diffusion.

Transient Conduction-Convection Equation BEM Solver

We have formulated and implemented a BEM formulation for the transient conduction-convection equation. This solver can be applied to solve the vorticity transport, energy transport, and mass transport equations. A paper on this formulation was presented at the InterPack'95 Conference (DeSilva et al. 1995).

Transient Navier-Stokes BEM Solver

The continuity (incompressible) and transient Navier-Stokes equations can be solved using the algorithms developed over the past two years. The equations are solved in vorticity and stream-function form. The

Poisson's equation, which governs the stream function, is solved using a normal and tangential gradient BEM formulation similar to the boundary integral equation for flow kinematics proposed by Skerget, Alujevic, Brebbia, and Kuhn (Chapter 4, *Topics in Boundary Element Research*, C. A. Brebbia, Ed., Springer-Verlag, 1989). This algorithm will be referred to as the kinematics solver. By specifying the domain vorticity and the boundary velocity, the kinematics solver can be used to solve for the boundary vorticities. Once the boundary vorticities are determined, the kinematics solver can be used to calculate the domain velocity field. In two dimensions, the vorticity is governed by the conduction-convection equation. This is solved by using the transient convection-conduction equation BEM solver that we developed. This solver will be referred to as the dynamics solver. The stream function and vorticity transport equations are coupled and are solved iteratively.

It should be pointed out that the governing equation for the vorticity is similar to those for the temperature and concentration. Consequently, the dynamics solver can be applied to solve the energy and mass transport equations in double-diffusive convection with cross diffusion.

5. Publications Under the Present Grant Cited in This Report

Chen, C. F. and Chen, C. C., 1994, "Effect of Surface Tension on the Stability of a Binary Fluid Layer Under Reduced Gravity," *Physics of Fluids* **6**, 1482-1490.

Chen, C. F. and Chan, Cho Lik, 1996, "Salt Finger Convection in a Stratified Fluid Layer Induced by Thermal and Solutal Capillary Motion," presented at the 3rd Fluid Physics Conference, Cleveland, June 13-15.

Chen, C. F. and Chen, Falin, 1996a, "Salt Finger Convection Generated by Lateral Heating of a Solute Gradient," presented at the 19th International Congress of Theoretical and Applied Mechanics, Kyoto, August 25-31, 1996.

Chen, C. F. and Chen, Falin, 1996b, "Salt-Finger Convection Generated by Lateral Heating of a Solute Gradient," *Journal of Fluid Mechanics* (submitted).

Chen, C. F. and Chen, W. Y., 1997, "Effect of Gravity Modulation on the Stability of Convection in a Vertical Slot" (in preparation).

DeSilva, S. J., Chandra, A., Chan C.L., and Lim, J., 1995, "BEM Analysis for the Transient Conduction-Convection in 2-D with Variable Convective Velocity" InterPack'95, Dallas, March 26-30.

DeSilva, S. J. and Chan, C. L., 1997, "High Rayleigh Number and Marangoni Number Simulations Using a Sub-Domain Method" (in preparation).

Jin, Y. Y. and Chen, C. F., 1996a, "Instability of Convection and Heat Transfer of High Prandtl Number Fluids in a Vertical Slot," *Journal of Heat Transfer* **118**, 359-365.

Jin, Y. Y. and Chen, C. F., 1996b, "Natural Convection of High Prandtl Number Fluids with Variable Viscosity in a Vertical Slot," *International Journal of Heat and Mass Transfer* **39**, 2663-2670.

Jin, Y. Y. and Chen, C. F., 1996c, "Effect of Gravity Modulation on Natural Convection in a Vertical Slot," *International Journal of Heat and Mass Transfer* (in press).

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